Nuclear and Particle Futures (N&PF) Pillar

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This document defines the N&PF Pillar as composed of four focus areas: Applied Nuclear Science and Engineering (ANS&E), Nuclear, Particle, Astrophysics and Cosmology (NPAC), Accelerators and Electrodynamics (A&E), and High Energy Density Physics and Fluids (HEDP&F). A team of Division Leaders drafted an initial vision of the pillar and presented it to the community in a series of focus area meeting of SMEs and pillar-wide town halls. Community input from this process was used to develop this final definition of the N&PF Pillar. The four focus areas are defined and discussed with an emphasis on the scientific scope of each focus area, the relevance to the Laboratory mission, areas of leadership, and interconnections between the focus areas.

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Nuclear and Particle Futures

1. Introduction

Los Alamos is the premier laboratory in the USA for all-things nuclear, with capabilities that are grounded in its LANSCE and DARHT facilities, its leadership in critical assembly work (now in Nevada), and extensive capabilities in nuclear experiment, theory, and simulation. The Nuclear and Particle Futures (N&PF) pillar is composed of 4 major thrusts: Nuclear, Particle, Astrophysics, and Cosmology (NPAC), Applied Nuclear Science and Engineering (ANS&E), High Energy Density Plasmas and Fluids (HEDP&F), and Accelerators and Electrodynamics (A&E). These four thrusts provide the underlying fundamental research and technological developments crucial to successfully advance Defense Programs weapons research, the nuclear component of threat reduction, and the pursuit of high priority fundamental research as identified in the strategic plans of Office of Science programs in Nuclear Physics, High Energy Physics, and Fusion Energy Sciences.

The complexity of nuclear weapons is such that expertise in many fields of physics and material science is required for a deep understanding of the current stockpile and how the stockpile will evolve in the future, encompassing both deliberately chosen modifications as well as natural changes with age. A fundamental understanding of the nuclear and plasma physics and their coupling under extreme conditions is needed to fully predict the behavior of dynamically assembled, fissioning systems. Neutron, and charged-particle transport and the associated cross sections need to be well in hand to understand the nuclear burn and boost processes, and to maximize the physics extracted from diagnostics. Understanding the high energy density plasma physics issues and fluid-like behaviors that drive the time evolution of a weapon is key to understanding nuclear performance. Complex material science and hydrodynamical mixing processes further complicate the physics, and the integration of science from the present Nuclear and Particle Futures Pillar with that from the other science Pillars has and continues to be essential to the success of the laboratory's mission. NPAC sponsors much of the fundamental research for the support of ANS&E, both of which benefit from technological advances in A&E. Modern diagnostic tools (e.g. XFEL, Neutron Scattering, electron and proton radiography) aimed at probing the mesoscale and its influence on material dynamics, require the technological advances that A&E provides (electron and proton accelerators) while supporting traditional particle generation for fundamental nuclear physics studies.

Just as understanding and stewarding our own stockpile as it ages is a priority, understanding an adversary's stockpile or clandestine weapon programs and the associated signatures and threats are also great challenges. ANS&E, HEDP&F and A&E research investigates the underpinning science, computational and experimental methodologies, and new diagnostics and techniques that are critical to advances in the nuclear component of threat reduction. This research, which is often a spinoff from the NPAC research, directly contributes to new methods supporting forensics, SNM detection and counterproliferation.

The Office of Science, Office of Nuclear Energy, and other federal agencies have developed strategic plans for research in areas of fundamental interest to the Laboratory: Nuclear Physics, High Energy Physics, and Fusion Energy Sciences. The thrusts of NPAC and HEDP&F support research that enables programmatic support by the Office of Science. ANS&E and A&E also support nuclear energy and fuel cycle research that plays key roles in energy security initiatives, as well as supporting the development

of novel power sources for other national security applications. ANS&E provides a foundational capability for nuclear safety in all Laboratory operations.
The thrust areas are interconnected in their research portfolios. NPAC develops enabling science ideas and drives technological developments, ANS takes direct advantage of these developments to investigate new ideas of relevance to weapons research and threat reduction. HEDP&F studies physics issues in the plasma regimes that can be created by the fission/fusion process and must take into account the interplay between the processes in burning plasmas. All of these activities benefit from advances driven by A&E, which is also a key research area that supports MaRIE and our radiographic capabilities.

Many of the capabilities in the Nuclear and Particles Futures Pillar find integration in the simulation capabilities that have been developed, which incorporate insights from experiment, theory and modeling, and algorithm work and take advantage of LANL's high performance computing hardware. This has created a validated integrated predictive simulation capability and enables the investigation of complex multi-physics systems and phenomena not attainable via experiments and theory alone.

2. Cross-Cut Against Major Laboratory Mission Goals

Mission Goals	ANS&E (applied nuclear science & engineering)	NPAC (nuclear, particle, astro & cosmology)	HEDP&F (high-energy density physics & fluids)	A&E (accelerators and electrodynamics)
Boost & Future Stockpile	Cross sections for RC & prompt diagnostics, outputs; neutronics codes; Nevada criticality experiments for validation	Nuclear physics, Rad Hydro, Mixing, Multi-physics, Turbulence, pRad, Uncertainty quantification; Fission Measurements (Chi-Nu, TPC, and more), Cross section measurements (including on short-lived states)	Plasmas, rad. flow, opacities, EOS; Turbulence, ejecta; Kinetic codes; Hydro & shocks, transport & burn codes	DARHT for implosions; LANSCE cross sections; Collaborations with Z machine ; HEPP
TN Burn	Thermonuclear cross sections; n, g imaging & radchem detectors for ICF	Rad Hydro, Mixing, Turbulence, Charged particle transport, Ab-initio theory for light-nucleus reactions; Nuclear reaction measurements on light nuclei	Thermonuclear burn initiation and propagation; mix; Warm dense matter	Trident laser-based particle accelerators for neutrons & ions; Collaborations with NIF, Omega, Z
Pu Science & Aging	Cross sections on decay daughter products (*e.g.* Am, Pu, U isotopes); Integrated simulations	Surrogate experiments at pRad; Fission, neutron capture & scattering	Ejecta source & transport	U1a: CYGNUS radiography; K-round for implosions; LANSCE cross sections;

		theory; Fission and reaction		HEPP for compression
SOO: Treaty Verification (remote sensing, safeguards & security, international relationships) & nonproliferation	MCNP code neutronics simulations; fission nuclear data for SNM detection; Nevada crits; Intrinsic Radiation (INRAD)	Detector development (liquid Cherenkov and scintillation, noble liquids), Muon tomography, active interrogation, Detector calibration, low background techniques, ultra-high resolution, Nuclear data measurements,	EMP & advanced threats	Active interrogation with advanced sources (lasers-based) & proton, gamma-ray, & neutron sources
SOO: Forensics (foreign weapon designs, sensors, material detection)	Code simulations & inverse analyes, nuclear cross sections & radiochemistry, fission	pRad; Cross section measurements, detector development, robotic systems, autonomous decisions in complex environments, persistent surveillance	Advanced designs	DARHT for implosions
Micron-challenge (dynamical materials response; manufacturing; turbulence; warm dense matter)	Nuclear fuels; fusion reactor first wall; eliminate/mitigate radiation damage for energy applications	Detector development; pRad ; eRad ; isotope-selective neutron radiography, radiation effects	Turbulence & materials experiments; warm dense matter; Ejecta source &	MARIE1.0. XFEL free electron laser; pRad; electron radiography (eRad); Lujan; M4 ; HEPP

		studies	transport	
Physics Beyond the Standard		neutrino physics, weak interactions, strong interactions, gravity, cosmology; symmetries;	Rad-hydro & burn for supernovae	LANSCE – ultracold neutrons, neutrino beam
Nuclear Matter in Extremes	Nuclear physics	QCD theory, lattice QCD, Cold Dense Nucleonic Matter		
Cosmic Explosions: Origins to Ashes	Cross sections, reaction networks, nuclear physics	supernovae modeling, nucleosynthesis	Rad-hydro & burn for supernovae	
Advanced reactors, fuel cycles, & spent fuel	Neutronics design, MCNP code, Nevada criticality experiments	pRad tomography of fuel pins , Uncertainty quantification	Fluid flow	LANSCE cross sections; material irradiations & MTS

3. Applied Nuclear Science and Engineering

Scientific Scope

One of the differentiating strengths of LANL is the application of nuclear science (broadly defined) to solving problems. Our strengths are embedded in the capabilities represented by our technical staff's breadth and depth, and are a product of our long-term national missions in the stewardship of the nuclear stockpile, as well as securing nuclear materials and providing defense against nuclear threats. This has given us the expertise and infrastructure to contribute to other areas where nuclear technology is critical in energy, safety, and applications of radionuclides and isotopes. The specific capability requirements in these areas are many, encompassing a broad range of technical disciplines, some highly specialized. These include nuclear weapons design and all aspects of understanding all types of nuclear processes (fission, fusion, capture, etc.) and energy production and transport associated with nuclear criticality and nuclear weapons. It also extends to strength in the technical capabilities that serve as diagnostics for these phenomena (prompt measurements of neutron and gamma-ray energy release, as well as indirect measurements such as radiochemistry). This encompasses the experimental determination of important data and validation of models, as well as underlying theory and advancement of models and databases that build on these technical areas. Overall, this focus area benefits from experimental and simulation capabilities and theory in nuclear physics, nuclear engineering, nuclear and radiochemistry, and weapons design.

Relevancy to Laboratory Mission and Areas of Leadership

Stockpile stewardship incorporates understanding of physical phenomena into simulations of nuclear weapons explosions, including the nuclear reactions that take place. Nuclear science supports this understanding by providing data on neutron-driven transformations such as energy production through fission and fusion reactions. Radiochemistry serves as one of the main diagnostics of weapons performance to characterize events; it is heavily reliant on accurate nuclear data. Nuclear science (both theory and experiment), therefore, supports both the underlying physics associated with explosion codes and the refinement of diagnostics that are used increasingly in the validation of models against our test history.

In addition to the critical role applied nuclear science plays in the weapons program, these capabilities provide support to understanding criticality relevant to nuclear energy and nuclear safety. Technical capabilities developed in association with the weapons program now play a large role in global security missions, including foreign weapons and assessment, nuclear forensics, and threat and device assessment associated with incident response. Knowledge of nuclear science and radiochemical separations enable other technology areas such as isotope production; LANL now serves as a major contributor to isotope production activities for the Office of Science. Growing areas of technical challenge in applied nuclear science involve management of nuclear materials, and detection and evaluation of materials (or devices) in processes, transport, or in managed storage (such as in treaty verification applications). Capabilities contributing to these missions include those exploiting a range of information associated with nuclear materials and processes (even drawing upon multiple types of measurements simultaneously), as well as interpreting this information, drawing upon knowledge of many of the nuclear phenomenologies identified previously. Applied nuclear science extends to the design and engineering of systems (for production, measurement, or material control) where knowledge of nuclear processes is important.

Key technical challenges have been identified in long-range programmatic requirements documents for the weapons program, including the *Secondary Assessment Strategy* [Verdon, et al. 2009], *Predictive Capability Framework*, *Primary Assessment Plan* [R. Reinovsky, C. Nitta, and M. G. Sheppard], *2010 Primary Assessment Plan* (U), Sept 2010, COPJ-2010-0442/LA-CP-10- 01220], the *National Boost Initiative Strategy Document* (U) [Beck, Chadwick, Graziani, Mehlhorn, Miller, Oct. 2007]), and the "Radiochemistry Roadmap" [Bredeweg and Kenneally, COCA-2011-049, LA-CP-11-01195]. Comparable technical challenges have been identified in documents associated with other missions, including the *Counterterrorism and Counterproliferation Management Plan*, NA-22 *MPD Annex*, and the *Isotope Production R&D Plan.* These capabilities are also highlighted in LANL's *Plutonium Science Roadmap*.

There are a number of key areas of technical capability that represent strengths for LANL, consistent with the integral role they play in enduring missions. LANL is home to significant strengths in both experimental nuclear science and nuclear theory and modeling that support many of the applications.

Theory and Simulation Capability

LANL plays a leadership role in simulation in the broader applied nuclear science and technology community, with capabilities that are grounded in measurements from LANSCE and other facilities, and from critical assemblies. This capability integrates Evaluated Nuclear Data File (ENDF) cross sections (which LANL leads for actinides, radchem detectors, and TN reactions), nuclear data processing using the NJOY code (a world-standard), and transport simulations using multigroup and Monte Carlo - MCNP is the world's gold-standard neutronics code. The isotope production code (IPC) also provides a unique radionuclide debris analysis capability. LANL's nuclear theory work in nuclear structure provides nuclear masses, deformations and fission barriers for astrophysical nucleosynthesis and NNSA applications; its nuclear reaction expertise is in Hauser-Feshbach and fission compound nucleus theory and in direct reactions, and in the R-matrix scattering theory which provides the basis for thermonuclear cross sections used in the NNSA labs. An area for focused attention here is the thrust in high-fidelity fission physics and simulation, where significant resources are presently being devoted in both theory and experiment, as well as in algorithm and data improvements for correlated particle production. A significant opportunity exists in the design and creation of new computational tools to utilize future extreme scale computer architectures.

Experimental Nuclear Science

LANL maintains extensive expertise in experimental facilities and measurements applicable to our applied missions. The Los Alamos Neutron Science Center (LANSCE) provides intense sources of neutrons and protons for a variety of applications, including isotope production and weapons nuclear physics research. Capabilities at the Weapons Neutron Research Facility and the Lujan Center contribute to measurements of neutron-induced cross sections associated with fission, light-nucleus thermonuclear reactions, neutron capture, etc. Los Alamos also operates the National Criticality Experiments Research Center (NCERC) in Nevada. NCERC operates critical assemblies that provide a fundamental capability for the nation to be able to perform critical, subcritical, and fundamental physics measurements. These sources support experiments that more closely represent the integral behavior associated with problems in applied nuclear science and engineering. LANL scientists also conduct research at facilities through the complex (and in some cases around the world), such as the National Ignition Facility (NIF), the Triangle Universities Nuclear Laboratory (TUNL), and Omega Laser Facility. An important aspect of experimental nuclear science is the ability to generate samples for study, using either stable or radioactive materials (including shorter-lived species that can be produced at LANL at the Isotope

Production Facility (IPF). Target preparation capabilities support these operations as does our broader capabilities in radiochemical separations and measurements, and prompt diagnostic capabilities.

Improved knowledge of nuclear reactions (and reaction networks) are required in such areas as transport calculations for the assay of nuclear materials, nuclear reaction rates for calculations of criticality, and models of stellar nucleosynthesis. Particular challenges include nuclear reaction properties for radioactive off-stability targets, correlated neutron and gamma emission from fission, and generating a high-fidelity understanding of fission, capture, and scattering reactions in actinides.

Detector technology

Radiation and particle detection is an area of expertise that is common across a number of topics in this focus area, both as the core of an experiment or as a diagnostic for a beam. As an enabling capability area, it is as distinct as the development of theory and models. Application and innovation of detectors to measure neutrons, charged particles, and gamma rays, as well as neutrinos, muons, and heavy ions, is crucial to experimental research in all the thrusts of Nuclear Futures; this capability plays a crucial role in Applied Nuclear Science and Engineering in such challenging applications as radiation detection, high fidelity experimental measurements, and diagnostics of nuclear systems. This expertise is a common thread, and advances and techniques developed for one measurement are often shared and utilized in others. Experimental expertise resident in one group or division can be used as a resource by others.

Challenges exist in the development and integration of detector capabilities suited to modern experimental facilities, often driven by needs of precision in measurement (spatial, temporal), or measurement of weak signals. Other technical challenges include integration of detectors into many different experimental conditions or environments, including field applications.

Weapons models and experiments

Los Alamos uses simulation codes and above-ground experiments to assess the stockpile and ensure its effectiveness. An understanding of nuclear physics related to fission and fusion burn are very important to these models; they are informed and validated through the examination (or reexamination) of prompt and radiochemical diagnostics, as well as energy outputs (n, □ etc). We seek to advance diagnostic and modeling capabilities (constrained by archival integral data or new small scale experimental data) to further validate and refine simulations of weapons performance. These tools and models are also significant in addressing global security applications. For example, we seek to enhance our capability to predict and/or interpret the outputs associated with unknown events, to diagnose potential threat devices, and to develop techniques for rendering such devices ineffective. Understanding the intrinsic radiation leakages from devices through experiment and simulation is also important for engineering applications.

As our use of diagnostic tools improves (either through inclusion of new diagnostics or reducing uncertainties associated with radiochemical measurements), technical challenges exist in adaptation of models to include improved understanding of physics, such as inclusion of late-time phenomenology. The need exists to improve our capability to predict and/or interpret the outputs associated with nuclear events, incorporating the impact of uncertainties on our assessments, and to provide technical solutions to measure and interpret these signals propagated in many different environments. This should include involvement in efforts to explore integration of data from different types of output measurements.

Material and device detection

From the inception of nuclear safeguards and nonproliferation efforts, Los Alamos has had enduring missions in the monitoring and measurement of nuclear materials. To address needs in these programs it is necessary to understand and exploit the fundamental methods of detection and measurement of nuclear materials; improvements may come from increasing the sensitivity of nuclear particle detectors, new types of active interrogation, non-nuclear detection modes, or advances in data analysis techniques or methods for data fusion. Simulations play a key role in the elucidation and interpretation of nuclear or radiological threat signatures and in designing the next generation of active and passive detection capabilities. Collectively, this knowledge is often incorporated into development and/or technical evaluation of systems concepts for active or passive detection of nuclear material. Applications of these methods extend from the design and implementation of cooperative safeguards programs, to the fielding of systems for transit or border protection.

Significant challenges exist in improving methods of detection and measurement, particularly for shielded materials. Advanced methods of measurement are likely to draw upon a more detailed predictive understanding of fission emission (prompt or delayed, induced or spontaneous) than we currently possess. We should continue to innovate in novel probes (e.g. muons) to characterize materials. There is also a need to develop alternative detection systems (e.g. neutron detectors not relying on He-3) that have optimal characteristics of sensitivity and energy resolution.

Nuclear reactor design and engineering

Los Alamos continues to advance the state-of-the-art in advanced nuclear energy concepts (including alternate designs), such as small modular reactors requiring novel engineering approaches. These capabilities also contribute to a strong complement of systems evaluation in nuclear energy systems, including modeling of the impacts of fuel cycles on proliferation risk and the rapid assessment of nuclear accident scenarios. The Laboratory maintains a core capability supporting the design, modeling, prototyping, and testing of compact reactors for applications such as space nuclear power or portable power generation for remote sites. The NCERC criticality site in Nevada provides a unique capability for the rapid testing of reactor concepts. Currently, there is a focus on special purpose and small modular reactor design for NASA and for DoD customers. Longer-range technical challenges exist in the development of predictive capability supporting the development of innovative fuel forms.

Irradiation capabilities

LANSCE serves an important role as a facility for utilizing neutrons in production applications, as well as in fundamental science roles, as do the critical assemblies at NCERC. LANSCE is home to the isotope production facility (IPF), a DOE-SC supported facility for the irradiation of targets for production of radioisotopes for research and sale. The Weapons Neutron Research Facility also serves a role in providing irradiation services for testing purposes, such as the accelerated neutron testing of semiconductor devices at the ICE (Irradiation of Chips and Electronics) Facility. In addition to providing services, LANL staff advance methods through significant improvements in the design of irradiation systems and targets, and in the development of methods for radiochemical separation and processing of isotopes.

There is significant interest in expanding these capabilities to address new needs. Efforts include evaluation of the promise of 25-kW irradiation capability at the Isotope Production Facility. Interest also remains in MW-level spallation capability at Area A at LANSCE for isotope production (e.g. Ac-225, a key target isotope for the Office of Nuclear Physics), fission fuels and cladding and/or fusion materials development (the Materials Test Station), or for nuclear physics experiments. All of these applications suggest significant interaction with the A&E focus area. As we develop new services and products associated with these facilities, it will be necessary to implement more innovative engineering approaches to generating sources (neutron, proton) with tailored properties. Significant challenges exist in development of novel target systems for isotope production, from predicting production pathways and rates, to devising novel separation chemistries to improve yields and reduce waste.

4. Nuclear, Particle, Astrophysics, and Cosmology

Scientific Scope

Research within the Nuclear, Particle, Astrophysics, and Cosmology (NPAC) thrust area seeks to answer the most fundamental questions in modern physics. From the origin and evolution of the universe, the origin of the matter antimatter asymmetry, the unification of the fundamental forces, the nature of nuclear matter at extreme temperatures, and the understanding of the most extreme environments in the universe. We now know that physics at the smallest scales determines physics at the largest scales. The scientific priorities within NPAC at LANL are aligned with the priorities established by national committees such as the Particle and Astrophysics Scientific Assessment Group (PASAG), the Nuclear Science Advisory Council (NSAC), the High Energy Physics Advisory Panel (HEPAP), the ongoing Snowmass Summer Study process, the Decadal Survey of Astronomy and Astrophysics, and the P5 Scientific Prioritization Panel. By attacking high priority fundamental physics NPAC attracts the nation's best scientists and postdocs to LANL, drives detector development, and develops new methods and techniques to measure and understand the subtle signatures of new physics. The strong coupling between NPAC and ANS&E ensures that a significant component of this development leads to new capabilities directly applicable to the Laboratory missions. The unique and diverse environment at Los Alamos enables many NPAC scientists to play leadership roles in broad areas of defense science. All of these aspects of the NPAC program play important and critical roles in the health of the Laboratory and impacts our ability to meet the next generation of challenges facing our Nation.

Relevancy to Laboratory Mission and Areas of Leadership

A strong NPAC capability will ensure a world leading capability in nuclear physics, high performance computing, and advanced detector development and provide a pipeline of excellence of our scientific staff at LANL into the future. Los Alamos has been a leader in NPAC science with internationally recognized expertise in neutrino physics, heavy ion physics, lattice QCD, fundamental symmetries, and astrophysics and cosmology. One of the LANL's unique strengths is the strong coupling of experiment, theory, and computational capability that allows us to solve complex multi-physics problems. Expertise and leadership in these areas of research require the development of advanced detectors, and novel diagnostics and measurement techniques, computational methods, and advanced simulation codes that are utilized by other LANL mission areas. Some examples include: 1) the development of proton radiography to radiograph explosive events and understand dynamic material properties and failure modes, 2) neutron resonance spectroscopy to dynamically measure the temperature inside materials, 3) muon tomography to search cargo and vehicles for special nuclear materials, 4) the measurement of neutron cross sections of actinides and of short-lived isomers are critical for nuclear forensics and stockpile stewardship, and 5) the development of radiation transport codes to model supernovae explosions are used to understand issues of relevance to the LANL weapons' community. It is clear is that LANL must retain a capability and active research program in nuclear, particle, astrophysics and cosmology is order to respond to new opportunities, retain first-rate staff and recruit and attract the next generation of scientists to the lab through post-doctoral programs. This scientific effort has significantly impacted the Laboratory through its high quality of science and its recruitment of theory post-docs into leading programmatic positions. Over the history of LANL the NPAC research program has attracted some of our nation's brightest scientists – NPAC at LANL currently includes 36 Fellows of scientific societies (and/or LANL Fellows) and has attracted well over 200 postdocs - of which 82 have stayed on as LANL scientists (many working in programmatic areas outside of NPAC).

Connections to N&PF Thrusts

NPAC research has had an enormous impact on the Laboratory as a whole, spurring innovation and discovery in areas of research from basic nuclear weapons physics to global security challenges. Here we delineate the connections between NPAC and the other thrust areas within the N&PF Pillar and with the broader LANL community. NPAC science and scientists have had a profound impact on other LANL mission areas.

NPAC and ANS&E: There are rich connections between NPAC and ANS&E, including nucleosynthesis of the lightest elements in the early universe, and heavy-element synthesis in astrophysical objects. The measurement of neutron cross sections of actinides and of short-lived isomers are critical for both astrophysics and nuclear forensics and stockpile stewardship. There are also strong synergies of ANS&E with neutrinos and fundamental symmetries where nuclei are used to study neutrino properties and fundamental symmetries.

NPAC and HEDP&F: There are deep connections being developed between NPAC and HEDP&F. These include both fundamental science applications including supernovae and astrophysics more generally, as well as nuclear diagnostics of high-energy density environments including NIF. LANL plays a leading role across the spectrum of basic to applied physics.

NPAC and A&E: Currently the main interconnects between NPAC and A&E thrust areas is the proton radiography facility at LANSCE, and the use of the LANSCE neutron beams and detectors to measure neutron cross sections for both fundamental and applied physics.

NPAC and LANL: Looking to the broader LANL community NPAC provides a wealth of expertise that is utilized within the Global Security PAD. From the early days when the Vela satellites were launched to monitor Soviet nuclear test and discovered gamma-ray bursts (the largest explosions in the universe) there has been a tight connection between the basic research and the global security missions of LANL. NPAC scientists are developing robotic systems capable of making autonomous decisions in complex environments (Thinking Telescopes) and pioneering persistent surveillance systems. NPAC science and scientists are uniquely qualified in the area of detector development for the detection of SNM. Particular areas of expertise include active interrogation systems, muon tomography, liquid Cherenkov and scintillation detectors, the development of a new class of detectors based on the emission of light and charge in noble liquids, low-background experiments and ultra-high resolution detectors based on semiconductors and bolometers.

NPAC at LANL plays a key role in large-scale computing, large data, and IS&T more generally at the laboratory. This broad program includes nuclear matter at extremes including RHIC physics and nuclear astrophysics, theory and simulation for Physics Beyond the Standard Model including neutrino physics and fundamental symmetries, and theory and simulations of compact objects and the early universe. LANL leads the SCIDAC-3 NUCLEI nationwide collaboration bringing large-scale computational capabilities to bear on nuclear structure and nuclear astrophysics. These capabilities play a key role in LANL more generally, particularly the NW program and global security.

Advancing our understanding of QCD and the fundamental properties of nuclear matter

Although there is strong evidence that Quantum Chromodynamics is the fundamental theory of the interaction of quarks and gluons, the basic building blocks of matter, we are far from being able to apply this theory to obtain high precision predictions of many properties of nucleons and nuclei. It is still not possible to start from the equations of QCD and completely explain the structure and properties of the proton, including its behavior in polarized reactions and in reactions at extremely high energies. Similarly, it is difficult to calculate the properties of the strongly-interacting plasma of quarks and gluon that existed in the early universe, shortly after the Big Bang, before its constituents formed into the baryonic matter that we see today. Precise knowledge of the QCD backgrounds is also vital to the searches for physics beyond the Standard Model. “Connecting quarks to the cosmos”, advancing our understanding of QCD through cutting edge theory and creative experimentation at the world’s premier collider facilities is at the heart of the NSAC long-range plan.

QCD is a remarkable and challenging theory that addresses phenomena ranging from the weakly-coupled regime, where perturbative techniques are applicable, to the strongly coupled regime, where lattice QCD is the most promising approach. In perturbative QCD, LANL is a recognized leader in the analysis of jets and their application to a broad spectrum of reactions ranging from electron-positron annihilation to nucleus-nucleus collisions at ultra-relativistic energies. Theoretical and experimental studies of the production and interaction of jets, heavy particles, and electromagnetic probes provide, at present, the most accurate determination of the properties of nucleons and nuclei. In lattice QCD we are becoming a center for calculations of matrix elements of strong, electromagnetic and weak interaction operators. The PHENIX team at RHIC spearheads the effort to determine how quarks and gluons formed in heavy-ion collision thermalize quickly into a nearly-perfect fluid state and what mechanism is responsible for the production and nuclear modification of heavy particles. In spin physics, in partnership with Fermilab, LANL scientists are leading the only approved experiment in the world to determine if the angular momentum of the sea quarks constitutes a sizable amount of the total nucleon spin. Our leadership and groundbreaking contributions to the field have been recognized through APS fellowship, LANL fellowship, Presidential and Early Career awards.

Today, the future of QCD physics is more exciting than ever. The rapid growth in computing power allows lattice calculations to confront problems ranging from the existence of new states-of-matter to searches for new physics at the intensity frontier. These anticipated developments are essential to establish that QCD is the correct theory of nature. Advances in modern effective theories of the strong interaction between quarks and gluons, such as Soft Collinear Effective Theory, allow for the first time high-precision calculations of particle and jet production at the world’s premier collider facilities. Such breakthroughs in analytic theory and simulations pave the way to the accurate extraction of the transport properties of hot and cold nuclear matter in nucleus-nucleus and proton-nucleus reactions at RHIC and the LHC. LANL scientists are well-positioned to play a leadership role in the future electron-ion colliders, such as the EIC and LHeC, where a broad range of fundamental questions will be addressed. Probing deep inside nucleons and nuclei, electron scattering experiments at the EIC will shed light on novel deeply-quantum phenomena and the dynamics of dense gluon systems. Experiments with polarized nucleons are poised to complete the 3-dimensional picture of the nucleon. These exciting directions are well aligned with the expertise of the LANL QCD theorists and experimentalists.

Institutional support for research outlined here will help maintain our leadership, national and international recognition in these areas.

Advances in QCD impact other thrust areas in the N&PF pillar and LANL mission goals. Nuclear and particle physics experiments benefit from developments in accelerator technology and provide the foundation for applied nuclear science and engineering. There is tremendous commonality in understanding the properties of strongly coupled quark-gluon plasmas and warm dense matter systems that span the range from dwarf galaxies to ICF capsules and nuclear weapons. Supercomputing, the cornerstone of lattice QCD, is central to the IS&T pillar. High-throughput data acquisition system development for the high luminosity and high multiplicity environments of proton and heavy ion collisions at Fermilab, RHIC and LHC directly benefit experiments at NIF. Advances in radiation resistant, high-resolution, and high-rate detector technology are also critical for non-proliferation and the harsh radiation environment of MaRIE.

Search for physics beyond the current standard model

The Standard Model of physics was established in the 1970s and unifies the weak, electromagnetic and strong forces, three of the four known fundamental forces of nature. Omitted from the Standard Model is the unification of these forces with gravity. Searches for Physics Beyond the Standard Model (BSM) seek to understand this further unification, explain why certain constants are as they are in Nature, and understand the origin, evolution, and fate of the universe. Understanding dark matter and dark energy, the origin of the matter anti-matter asymmetry (the universe is composed almost entirely of matter whereas the laws of physics are nearly invariant with respect to matter and antimatter), and searching for evidence of new particles and new interactions are at the heart of BSM physics. The questions pursued in this frontier are set by the national and international community of scientists, and by the US national funding agencies NSF and DOE Office of Science. Generally the questions in this area are broad and cut to deep mysteries in our understanding of Nature at the boundaries of the Standard Model and the grammar we use to describe it – quantum field theory and General Relativity.

Current LANL experimental efforts are focused on three major research fronts: the origin of the matter anti-matter asymmetry, the nature of the dark matter, and searches for new "dark sector" particles. LANL is either leading or playing major roles in three experiments designed to understand the origins of the observed matter antimatter asymmetry. The neutron EDM (electric dipole moment) experiment seeks to measure an electric dipole moment of the neutron as small as ~10-28e-cm, two orders of magnitude better than current limits. Failure to observe such an edm will essentially rule out electroweak baryogenesis as an explanation of the observed matter dominance of the universe. Another hypothesis for generating the matter anti-matter asymmetry is known as leptogenesis. The MAJORANA experiment (which seeks to determine if the neutrino is its own antiparticle) and the Long Baseline Neutrino Experiment (which seeks to measure the neutrino mass hierarchy and CP violation in the neutrino sector) are the forefront of this research (these experiments are described in more detail below in the "Neutrino Properties" section). In the dark matter arena, LANL scientists have developed a method to utilize the scintillation properties of liquid argon to design a scalable experiment sensitive to dark matter particles with masses of 30 GeV to above 1 TeV, while the HAWC gamma-ray experiment, will be sensitive to dark matter in the mass range of 1 TeV to 100 TeV, and for lower mass dark matter particle LANL scientists are using the MAJORANA experiment to search for dark matter particles with masses as low as ~5 GeV. LANL scientists are leading the effort to use existing neutrino detectors such as MiniBoone, MicroBoone, and LBNE to search for new "dark sector" particles.

A unique strength of the LANL theory and experimental program are their close coupling. As with the experimental program the LANL theory program is developing theories to explain the matter anti-matter asymmetry and unique methodologies to link experimental results to these theories. In particular, LANL theorists are using lattice quantum chromodynamics to compute from first principles the matrix elements of quark operators inside a neutron, which are needed to translate measurements of the neutron edms into useful statements about BSM physics. Searching for BSM physics at the highest energy interactions available on earth, LANL theorists are developing new theories and strategies to search for new particles at the LHC and using data from the LHC to constrain theories of dark matter, of neutrino self-interactions, and of new interactions that would appear in the decay of a neutron. LANL scientists are using the Helium burning phase of red-giant stars to obtain the strongest constraint on the interactions of the axion - a strong dark matter candidate – with the photon. They are proposing models of a non-black hole final state of gravitational collapse, consistent with quantum mechanics, and determining its observational signatures. LANL theorists are studying non-equilibrium phase transitions and particle production processes relevant for the early universe, the quark-gluon plasma, and high-energy jets arising from compact sources and astrophysical plasmas.

In the next decade experiments may surprise us with unanticipated discoveries and will certainly force us to abandon many cherished theories. The LHC will soon operate at higher energies, collect significantly more data, and provide a definite verdict on many theories of BSM physics. We seek to play a major role in a future national dark matter program, bring to completion our work on neutron EDMs, and carry out sensitive searches for dark sector particles in future experiments as they come online (MicroBoone and LBNE). The US will soon decide on its next generation of dark matter experiments and LANL should play a central role in the development of a massive detector using liquid argon with the CLEAN or DarkSide collaborations. In astrophysics and cosmology we should continue and expand our role in the LSST and other large-scale structure surveys (that are based in Mexico) to study dark energy and cosmic evolution. In high-energy astrophysics we should continue our leadership in gamma-ray astrophysics with a successor to HAWC that could open the extragalactic universe to study at the highest energies. At lower energies LANL should lead a new space-based instrument to study the evolution of the elements.

BSM physics has strong connections to other LANL mission areas. Connections to the IS&T Pillar include, the use of LANL's large-scale computational capability to understand supernova neutrino oscillations, lattice quantum chromodynamics, N-body gravitational simulations and the analysis of large data sets. Advances in non-equilibrium field theory and understanding phase transitions will be of benefit to MaRIE and other LANL institutional programs. Detectors developed to search for high-energy gamma rays, dark matter particles, and neutrinos provide a strong connection to the detection of SNM and the Global Security mission of LANL.

Determine neutrino properties to elucidate physics beyond the Standard Model

The discovery of neutrino oscillations was a discovery of physics beyond the standard model. Neutrino physics at Los Alamos now centers on measuring the nature of this beyond standard model physics to understand the deeper theory of the fundamental forces that define our universe. Searches for neutrino-less double beta-decay aim to determine whether or not the neutrino is its own anti-particle and involves detectors of unprecedented purity and sensitivity. Measurements of the neutrino masses and number densities are at the forefront of today's cosmology. Light sterile neutrinos may be a major component of the dark matter. Neutrinos are crucial to successful supernova explosions and nucleosynthesis and may also be the key to understanding the matter anti-matter asymmetry in the universe. In short, neutrino physics may hold the key to understanding the question, *Why are we here?* At the same time neutrino physics provides a excellent example of the beneficial connections and natural synergies between the different parts of the NPAC pillar. It brings together experimental and theoretical expertise in particle and nuclear physics, astrophysics and cosmology, as well as state-of-the-art detector technology and supercomputing.

LANL scientists are leading several high-profile neutrino experiments including the MAJORANA Demonstrator neutrino-less double beta-decay experiment at the Sanford Underground Research Facility (SURF), the MiniBooNE and MicroBooNE experiments at Fermilab, the LBNE experiment employing both laboratories, and the CAPTAIN experiment being developed at LANL. These experiments address the major scientific questions including: *What are the absolute neutrino masses? How many neutrino mass states exist? Are neutrinos Majorana (their own anti-particle) or Dirac particles? What are the neutrino electromagnetic properties? Does CP violation occur in the lepton sector and do neutrinos interact by new forces of nature?* LANL theorists have led the world in supercomputing simulations of neutrino flavor transformations in supernova environments and presently lead the efforts within the LBNE collaboration to model detector signatures of this physics. They have also established how current and future experiments, from long-baseline oscillations to the LHC, can be used to search for new physics in neutrino-matter interactions. They have also demonstrated the impact of neutrino oscillations on r-process nucleosynthesis and characterized the signatures of relic neutrino energy densities in the Cosmic Microwave Background.

Experiments in this area of research can take a decade or more to come to fruition, thus much of the future work will be a continuation of current efforts. The LBNE project is scheduled to begin data taking in 2023. The MAJORANA project will merge with other efforts around the world and construct a tonne-scale neutrinoless double beta decay experiment.

The neutrino physics program at LANL has a large impact on the Laboratory by performing world-class fundamental science, developing world-leading detector technologies and computing models, and attracting top scientific talent to Los Alamos. Neutrino research has had a storied history at the laboratory, including a Nobel Prize for the discovery of the neutrino. The LANL neutrino program continues this tradition of excellence.

Understand Cosmic Explosions: From Origins to Ashes

The study of astrophysical cosmic explosions is one of the fastest growing areas of astronomy (ranking at the top of recent NSF/NASA and astronomy priorities lists) with many of the new and upcoming NSF/NASA-funded telescopes focusing on cosmic explosion observations attracting thousands of PhD scientists (including 40 active academy of science members) throughout the world. Important astronomy questions include understanding the origin of these outbursts: their progenitors and engines, as well as using these transients to probe their surroundings (e.g. the early universe). Astrophysical cosmic explosions are also probes of matter at extreme conditions including general relativity, nuclear physics and particle physics and make ideal laboratories to study this physics.

Los Alamos holds a special niche in studying cosmic explosions as it brings together the basic physics expertise, integrated models, experimental leadership, and data analysis techniques to bear on this problem (note: nearly all academy of science members at LANL have worked on this topic at some point). Understanding observations of cosmic explosions requires a broad set of LANL core physics all tied together in multi-physics high-performance computing applications: nuclear and particle physics, radiation and particle transport, turbulence, plasma physics and magneto-hydrodynamics and atomic physics. LANL scientists are able to leverage LANL mission capabilities in these fields and past work has shown a symbiotic relationship between cosmic explosion studies and mission science. Similarly, observations of cosmic explosions require the latest in source detection and data-mining resources. Current projects include studying the broad range of diagnostics in cosmic explosions (both from a theory and observational side): nucleosynthetic yields, neutrino spectra, thermal and non-thermal photon emission, magnetohydrodynamic effects and particle acceleration in both the outbursts and the remnants of these explosions, cosmic rays, and compact object characteristics. LANL is unique in its ability to cover all of these aspects at a single institution.

LANL has established itself as major player in many aspects of cosmic explosion observations. LANL should both expand its role and grow its capabilities in future observational projects. Strongly tied with this is LANL's leadership in observational programs (such as HAWC and RAPTOR) and LANL will continue to grow its role in ground-based missions such as Caltech's iPTF and the future LSST as well as NASA missions such as Swift and NuSTAR. With the upcoming plans for ground- and space-based telescopes, the amount of data on cosmic explosions is growing rapidly and LANL must position itself to take full advantage of this data (both from a theory and observational standpoint). Tying this academic work back to the program ensures that LANL's physics expertise remains top-notch.

The work in astrophysical cosmic explosions has already demonstrated a strong synergy within the N&PF Pillar, the broad LANL mission and the academic community. For example, the work on supernovae has strong interaction with the HEDP&F community (with many overlapping base physics focus areas) and the broader mission science community: working closely with ASC and campaigns to tie academic expertise to mission-relevant problems, leveraging off of and developing software and V&V tests for these communities, and dominating the recruitment and training for X-division. This effort already brings in over $1M in post-doctoral support for cosmic explosion-related projects and a growing number of scientists funded by the program (roughly 9 in XTD, XCP, CCS) working on cosmic explosions during their 25% time focused on career development (~$1M additional support). This already strong synergy can still grow extensively. The cosmic explosion effort connects directly to the NPAC effort understanding unstable nuclei and, as such, ties with the ANS&E and A&E efforts within N&PF and has broader ties with the laboratory mission. The full cosmic explosion effort has the potential to strengthen these ties (e.g. increasing the synergy in the nuclear physics and forensics field) as well as build new physics ties such as plasma and magneto-hydrodynamic physics and charged particle transport. This computational effort has ties to the IS&T pillar. Cosmic explosions play a growing role in global security in data mining (tying to the IS&T pillar) and data acquisition. At LANL, NSF, NASA, and DOE Office of Science have funded the cosmic explosion effort and the large collaborations developed by the LANL cosmic explosion community connect LANL to hundreds of academic scientists around the world.

The Origin, Evolution, and Properties of Atomic Nuclei

Nuclear reactions drive stellar evolution, create the largest explosions in the cosmos, populate the universe with a diversity of elements, power reactors, image the functioning of biological processes, and provide radio-pharmaceuticals that directly target diseased organs. The arrangement of the neutrons and protons in complex nuclei gives rise to regularities and periodicities that determine nuclear masses and shapes, as well as nuclear reactions and decay processes. Yet recent experiments in nuclei have revealed surprising *irregularities* that cannot to be explained by current theories. For example, measurements in exotic nuclei question whether we fully understand how the fundamental interactions determine the structure of matter when the number of neutrons and protons differ significantly. Such findings challenge our ultimate goal of developing a predictive and accurate framework for nuclear structure and reaction theory. While some of these challenges remain squarely in the realm of nuclear physics, many are interdisciplinary, involving fields ranging from hydrodynamics to bio-medicine.

Los Alamos has a long history in nuclear physics. The facilities at LANSCE are one-of-a-kind for studying neutron-induced reactions including fission, capture, and neutron scattering on stable and unstable nuclei. The unique tools available at LANSCE allow us to study the formation of the elements, important detailed properties of the fission process, and the structure of nuclei. The nuclear theory program at LANL addresses the underlying structure and fundamental properties of nuclei, their interaction with matter in extreme environments, and the use of nuclear reactions as diagnostics for physics ranging from the weapons program to particle physics. The Isotope Production Facility (IPF) at LANSCE creates macroscopic quantities of radioisotopes for the international community in medicine, industry, and science. External facilities at universities and other national laboratories offer beams of stable and unstable heavy ions for charged-particle reaction studies to complement the neutron-induced reaction studies at LANSCE. Together, these neutron and charged-particle facilities enable us to probe the interplay between the macroscopic behavior of bulk nuclear matter and the microscopic features of fermionic systems.

LANL plays a leading role in large-scale simulations of nucleonic matter and nuclei, leading the SciDAC-3 NUCLEI project (computingnuclei.org) involving 19 universities and national labs. Theory and computation tie experimental nuclear physics to astrophysics including neutron stars and supernovae, and physics beyond the standard model that can be addressed in nuclear experiments.

The national nuclear physics community, funded by DOE/Nuclear Physics, has undertaken the construction of the Facility for Rare Isotope Beams (FRIB). FRIB will provide precision measurements on isotopes beyond the reach of our current facilities, enabling studies of rare isotopes that are important to nuclear astrophysics, fundamental interactions, and applications for society. As LANL’s nuclear theory program continues to develop an *ab initio* description of nuclei, it will provide input and guidance to this precision experimental frontier. The nuclear science community at Los Alamos is taking advantage of advances in experimental and theoretical techniques to allow us to play a leadership role at FRIB.

While understanding the evolution of atomic nuclei is a fundamental scientific endeavor in itself, it also serves as an irreducible component of our programmatic efforts in LANL's mission. In addition, we contribute significantly to advances in other N&PF disciplines. The ANS&E nuclear energy and defense missions rely on properties of nuclei, both for performance and diagnostics. Nuclear physics studies play a crucial role in developing and validating the tools required in these sister disciplines of basic and applied NPAC science. For example, in HEDP&F we are directly involved in the development of new nuclear-based diagnostic tools for the NIF, and in code testing through comparison to astrophysical events and the corresponding nucleosynthetic yields. Advanced gamma, charged particle, and neutron detector techniques have been similarly important in A&E.

5. Accelerators and Electrodynamics (A&E)

Scientific Scope

Accelerator and Electrodynamics Science and Technology is a core capability that drives a wide range of LANL mission relevant portfolios, many of which belong to the other elements of the "Nuclear and Particles Futures" Focus area. A&E enables charged particle acceleration through controlled utilization of electromagnetic fields, supporting National Security missions involving radiographic imaging, remote measurements of electromagnetic signatures, sources of directed energy (for probes and defeat), and development of new capabilities such as radiation therapy and irradiation/sterilization of materials while furthering fundamental research in supporting key technologies. Of the NNSA laboratories, LANL is alone in maintaining a world-leading accelerator capability (LLNL has largely moved to lasers and SNL to pulsed power). Because DOE Office of Science accelerator laboratories lack appropriate personnel and the infrastructure needed to address national security-based accelerator missions, it is essential that the Laboratory carefully manage its accelerator and electrodynamics capability for current and emerging missions. To maintain leadership in mission relevant areas of this field, we must commit and dedicate appropriate resources in selected priority areas to ensure sustained availability of existing technology-capabilities, and seize opportunities in the nuclear deterrence and global security mission areas, while supporting the science-of-signatures and materials pillars.

Relevancy to Laboratory Mission and Areas of Leadership

A broad spectrum of accelerator and electrodynamics technology has been applied to a wide range of mission relevant programs and scientific disciplines, such as stockpile stewardship, material science, nuclear physics, national security and radioisotope production. As a key enabling technology, our demonstrated capabilities in the construction and operation of such devices has created a significant infrastructure providing the depth required to enable our R&D activities. The following major capability areas in the accelerator and electrodynamics focus area contain key elements of a strategy to meet the needs of the institution due to their mission relevance, strength of available technical expertise, programmatic growth prospects, and transformative nature.

Linear Accelerators

High average power proton linear accelerator (linac) technology is an area where LANL demonstrates world leadership. Conventional radio-frequency driven accelerators have been the workhorse of nuclear science and material science, as demonstrated by the capabilities of the LANSCE facility where an 800-MeV high-average-power proton linac generates both primary proton and secondary neutron particle beams for mission critical applications. These applications include beams for nuclear cross-section measurements (of critical importance to stockpile stewardship), proton radiography, radio-isotope production in support of fundamental research and to support the world-wide medical community-needs, as well as secondary beams for materials studies (Lujan Center). Technological advances with linacs opened up two entirely new applications: accelerator-driven production of tritium and accelerator-driven systems for energy production.

LANSCE maintains world-class, reliable operations in support of a broad portfolio of fundamental science and applied R&D. Recent investments to ensure the long-term continuing operation of LANSCE and to re-establish high-average-power operations is a strategic focus area and will enable even broader applications such as: high-energy isotope production for medical and weapons applications, intensity-frontier nuclear and particle physics, high-power spallation target testing, fission/fusion materials testing, and alternative fuels irradiation for reactor conversion. Development of a long-range plan that takes advantage of our significant investments to maintain operational flexibility for a wide range of applications and users at LANSCE is a high priority.

Los Alamos also demonstrates world-leadership in free-electron laser (FEL) science and technology, with concepts being vigorously pursued today. We enjoy a technical edge in the area of high-brightness electron beams. The photo-injector, invented at Los Alamos, is the electron source of choice for nearly every high-brightness electron accelerator in the world today, and we continue to lead in the theory, design, and operation of such injectors. Sub-picosecond chicane bunch compression was first demonstrated locally and is used at all FEL facilities. Our numerical accelerator and FEL modeling capabilities are highly regarded, leveraging a unique combination of supercomputers and collaborations with all major high-performance numerical accelerator teams world-wide. Many diagnostics and diagnostic measurement techniques for high-brightness electron beams were pioneered at Los Alamos, including optical transition radiation (OTR).

Much of the Laboratory's expertise in high-brightness electron beams has been sustained and extended through the ongoing Navy FEL program and supporting projects, leveraged with support from institutional LDRD. We are applying this expertise in electron linac technology to enable the new Matter-Radiation Interactions in Extremes (MaRIE) facility that will include a 12-GeV electron linac driving an x-ray free-electron laser (XFEL). Here, the primary focus has been on the generation and acceleration of high-quality electron beams through innovative manipulations of the fundamental beam properties. However, LANL leadership in electron-linac technology also continues through the development of high-average current cathodes and novel RF structures such as superconducting spoke-resonator and photonic band-gap cavities. High-current induction linacs require reliable cathodes to produce kilo-ampere electron beams. Photo-injectors that produce beams for FELs require lower-current, but significantly higher beam-quality electron beams. Advances in cathode technology will impact all electron-based Laboratory accelerator programs, including the Navy FEL, DARHT, and MaRIE. Additionally, non-invasive diagnostics that are being developed are essential for commissioning new concepts. LANL offers unique capabilities to that end, including Smith-Purcell based diagnostics and emerging concepts that exploit edge radiation.

LANL's investment in the development and utilization of DARHT has led to an unprecedented capability in high-dose radiography. Continued investment in developing the components, systems, and methods to improve the reliability and uptime of this unique asset should be a programmatic priority along with basic research to support improved spot sizes and reproducibility through improved target designs, as well as understanding multi-pulse beam/target interactions. High-current electron beams from induction linacs such as the DARHT facility are critical to meeting the milestones of the stockpile stewardship program. This category of accelerator relies on high-performance, pulsed-power systems to supply the energy to accelerate the beam with a time structure capable of measuring hydrodynamic performance of a test object in a matter of microseconds using reliable thermionic cathodes that generate the kilo-ampere beams.

While DARHT is already being successfully utilized in support of the Stockpile Stewardship Program, the overall mission set of DARHT can be expanded to meet new mission-critical needs. Sufficient beam energy exists to enable experiments in high energy density physics of fundamental physics interest and in support of warm-dense-matter experiments relevant to the weapons program. Additionally, DARHT could be used as an intense source of terahertz radiation to enable a number of experiments in support of the Global Security (GS) mission of the laboratory.

Linear accelerator technology is also being applied to meet NNSA's Global Threat Reduction Initiative (GTRI) by helping to reduce the U.S. dependence on foreign reactor-based sources of Mo-99 by leveraging key electron and proton accelerator technologies. Proof of principle experiments being performed at LANSCE today and others planned using future high-power beam capabilities can contribute to interim production of Mo-99 for the nation and serve as reserve capacity once commercial entities come on line that provide sustainable long-term Mo-99 production. Other accelerator technology based, cross-cutting, mission-driven capability areas that must be invested in include compact accelerators for radiography, for use as materials probes, and for explosives active interrogation and nuclear material and device detection.

Laser Acceleration

Significant advances are being made in laser acceleration. Plasma is the ultimate medium where the highest acceleration gradients and largest currents can be supported, motivating the worldwide research in advanced plasma-based accelerators. Advanced high-gradient, high-current particle acceleration schemes require high power densities delivered into small volumes. This makes high-power, high-energy, short-pulse lasers a natural choice to drive such schemes. Efforts in this area are growing and generating increasing interest at major institutions known for conventional acceleration technology. Through a series of cutting edge experiments and utilizing the capabilities developed and utilized in the LANL Trident laser facility, LANL has positioned itself as one of the world leaders in laser-driven ion acceleration. As a byproduct of its work and capabilities on relativistic laser-matter interactions, LANL has gained world leadership in the generation of coherent radiation from solid-density laser targets in the form of laser harmonics extending to multi-keV x-rays.

Ion-beam pulses have been successfully produced and transported using the present generation of high-energy, high-power short-pulse lasers. These beams, which, in principle, can be viewed as laser-driven, plasma based linacs that operate over ~ µm lengths, are born in sub-ps pulses, with very large ion numbers (up to ~ 1013/pulse), high laser-ion conversion efficiency (up to ~ 10%) and large ion energies (MeV to GeV). Due to their unique and complementary characteristics relative to conventional accelerator technology, these ion beams are very promising for several applications. To date, lasers have been most utilized as light sources in HED experiments by generating incoherent atomic radiation. A frontier area is the development of a laser-based XFEL. LANL should monitor and potentially partner in this area. Other novel laser-driven multi-spectral UV and x-ray sources requiring frontier science for their development are emerging with unique abilities as diagnostic tools for dynamic experiments.

Applied Electrodynamics

Applied electrodynamics science and technology has been broadly applied to meet significant technical challenges in support of LANL mission-critical programs. Los Alamos' work in electrodynamics has advanced the field over the last several decades. The majority of work in this area is enabled by the relatively unique overlap of national security missions and broad, multi-disciplinary and foundational technology expertise at Los Alamos. LANL electrodynamics efforts can be broadly categorized into three main areas: pulsed power, RF sources and components, and THz/meta-materials.

Work began decades ago to support the weapon programs' analysis of electromagnetic pulse (EMP) effects from atmospheric nuclear blasts. This work was motivated by availability of RF tubes developed for a pulsed linac that contained the highest power available in short pulses. This led to other classes of directed-energy research, including the direct use of accelerators to drive FELs and several non-directed energy electrodynamics activities as well

High Explosive Pulsed Power (HEPP) is an experimental platform with has applications in both the weapons and global security communities. We have had a long history of experimenting with and simulating magnetic flux compression generators (FCGs) to drive relevant physics loads. There is still interest in utilizing the capability to drive significant volumes of matter into the warm dense regime, identifying a strategy that supports the capability while meeting mission need is critical to the future sustainment of this capability.

High-power microwave (HPM) work has been funded by the U. S. Department of Defense and other government agencies for decades. With our combination of fundamental materials, nonlinear dynamics, and complex engineered systems expertise, the Laboratory can uniquely address the very complex effects and damage-assessment issues complicating the HPM program advancement.

In the area of pulsed power, the Laboratory is a leader in solid-state diode-directed Marx generators and air-core transformers, superluminal RF sources, and nonlinear transmission lines. In the area of RF sources and components, the Laboratory is recognized in the use of photonic band gap structures for components such as channel drop filters and for interaction structures in electron-beam RF sources. Uses of applied electrodynamics in support of national security missions typically focus on radar, communications, and spectroscopy. Emerging defense and intelligence requirements include stealthy (the point of origin cannot be located or the radar signal cannot be detected) and high-resolution radar, low probability of interception yet ultra-high bandwidth communications, and being able to extract new signature information with lower-power and higher-standoff spectroscopy. These capabilities additionally support the Laboratory's strategic programmatic focus areas in persistent surveillance and treaty verification. LANL also has expertise in the generation and transport of sheet electron beams for RF sources in the W-band (90-100 GHz). Presently, the Laboratory leverages the combination of the DOE investment in the Center for Integrated Nano-Technologies (CINT) with the strong RF capabilities in AOT, IAT, and ISR divisions to develop new RF and electronic solutions based on THz and metamaterials to address mission needs, such as electrically small antennas, stealth technologies, and future novel metamaterial- based accelerator beam diagnostics.

Integration Opportunities and Capability Enhancement

At present, insufficient integration exists between the various mission elements of the accelerator and electrodynamics capability (DARHT, LANSCE, Trident, AOT, ISR, WX) needed to steward and sustain long-term technical growth and excellence. A strategy is needed to identify specific areas of technical cooperation and integration between the mission elements to enable new capabilities that otherwise would be difficult to develop by the individual entities. Some potential areas of technical overlap have already been discussed earlier to support, for example, the GS and GTRI missions of the Laboratory. Broader participation in the development of the MaRIE concept is another recent example.

Finally, there are realistic approaches for involvement in the DOE Office of Science accelerator programs including the Muon Accelerator Program (MAP), FACET-II (at SLAC), and the Advanced Superconducting Test Accelerator (ASTA at FNAL), as well as other national laboratory, industry, and university partnerships that can be used to enhance our overall accelerator and electrodynamics capabilities. The Laboratory can leverage a combination of unique personnel or technology capabilities and mission space to enter into each of these new projects; this, in turn, can be used for additional cutting-edge capability development and establishing collaborations with colleagues at Office of Science accelerator laboratories and elsewhere, that will provide opportunities for low-cost reach-back to support LANL accelerator programs.

6. High Energy Density Physics and Fluid Dynamics

Scientific Scope

High energy density physics (HEDP) is broadly understood as the study of systems where matter is subjected to extreme conditions, resulting in pressures at or above 1 Mbar, and its scientific foundation is built on a broad area of plasma physics including relativity, quantum and statistical physics. Fluid dynamics describes fluid motion and material mixing which underpin modern technologies and science ranging from relatively benign and slow effects in climate, to reactive and fast energy release. These scientific disciplines are crucial in understanding energy production in military and civilian applications.

Relevancy to Laboratory Mission and Areas of Leadership

HEDP&F are critical disciplines to the LANL missions in national security, energy, threat reduction and basic science. HEDP&F pose significant and exciting scientific challenges critical to research in many areas, such as nuclear weapons (e.g., boost), Inertial Confinement Fusion, astrophysics, etc. Los Alamos has a long history of research and accomplishments in HEDP through basic plasma science, pulsed power research, inertial confinement fusion program, and above ground experimental program for the stockpile stewardship effort. We have access to world-class experimental facilities such as our medium scale Trident laser, and outside large scale ones - NIF, Omega, and Z. In addition to our molecular dynamics and radiation hydrodynamics simulation codes, our plasma modeling and simulation capabilities are extensive ranging from kinetic particle-in-cell with explicit and implicit Maxwell solvers, hybrid with multiple time scales, and magneto-hydrodynamic simulations. Our state-of-the-art 3-D particle-in-cell simulation code VPIC with its highly optimized numerical algorithms with respect to modern computing architecture is a best-in-class capability in plasma physics modeling at grand-challenge scales. Moreover, our legacy 2-D simulation code Merlin has extensive and well-validated physics packages for simulations of charged particle beam physics and electromagnetic interaction. These cumulative knowledge and capabilities have earned our Laboratory a reputation being a center of excellence for high energy density science research.

LANL's predictive capabilities in the fluids research areas is supported by its strength in the underpinning theories, supporting experiments (detailed diagnostics and experimental capabilities at low and high energies), numerical simulations such as Direct Numerical Simulation, Mix-Modeling (e.g. RANS, LES, ILES, FNSA), and advanced fundamental theories (e.g. PDF methods and spectral). This integrated portfolio seeks to continue to build solidly on theory, simulation, and experimental programs allowing for leading edge predictive capability well suited to take on the industrial and National security needs of the nations.

Many reports have stated the exciting scientific challenges in HEDP&F, such as the "Research Needs for Material Mixing at Extremes" (LA-UR-11-02563), the "Basic Research Needs for High Energy Density Laboratory Physics" (US DOE and NNSA, 2010) and the "Science of Fusion Ignition on NIF" (LLNL-TR-570412). In the Defense Programs (DP) area, HEDP&F is critical to the 2014 and 2018 Level-1 milestone (Predictive Capability Framework peg-posts). More broadly, multiple high-level reports and panels have stated and described the critical need for HEDP research in DP, such as the 2008-9 ASC national "right sizing" effort, the 2009 Science Campaign capability planning, and the FY 2012 Stockpile Stewardship Management Plan report to Congress (April 15, 2011).

Addressing the challenges posed above requires research aimed at closing scientific gaps in HEDP&F properties and processes. The laboratory has had a leading role in many of the technical areas and will need to continue it leadership to fulfill its mission requirements. Five areas of leadership in HEDP&F have been identified.

Relativistic laser-plasmas and charged particle beam generation and applications

LANL had a historical role with the Bright-Source laser family at the beginning of the era of relativistic laser plasmas, i.e., when lasers became sufficiently intense to be able to drive electrons to kinetic energies in excess of its rest mass. In the 1980's LANL was one of the selected few laboratories worldwide with such capability. Concurrently, the LANL capabilities in supercomputing, kinetic modeling (specifically PIC) and atomic physics modeling provided the basis for leadership then. In the 1990's, the field took a quantum step forward based on the results from the NOVA PW laser facility and increasing application of kinetic plasma modeling. Since then, building on those results, LANL has regained leadership in this field, specifically in the interaction of short-pulse lasers with solid-density plasmas, based on the developing capabilities of the medium-scale Trident Laser Facility, and our world-class kinetic modeling capability embodied in the VPIC code. LANL has become a center of excellence in laser-driven ion acceleration, discovering and developing new acceleration mechanisms and even reaching a new regime with the potential of achieving record efficiency in ion acceleration. This regime is already being exploited to develop the next generation of compact, high-current, high-gradient ion accelerators, intense neutron-beam sources and coherent light sources. LANL is uniquely positioned for leadership in this scientifically vital and rapidly evolving technology and its applications.
In the years ahead, the Laboratory should have a developmental emphasis in maturing this science and technology area to greatly open up credible HEDP applications. To that end, beam conditioning, transport, characterization, and reproducibility should be pursued.

Fluid dynamics, turbulence, mixture

Los Alamos has long been a leader in the following areas of importance for mixing and turbulence research: 1) Interfaces (the science of mixing interfaces, e.g. ejecta, shock/density, solid/liquid, and material transport); 2) Evolution of mix morphologies (mingling of fluids increases interface areas and generates mix morphologies that are complex but control key exchange processes such as mass, momentum and energy); 3) Transport (the movement of material across a physical domain remains one of the most difficult problems due to physical processes that take place during the move, and its representation on the computer); 4) Reactions (chemical and nuclear – how to properly represent sub-grid processes); 5) fluid/structure boundary interactions that include multiphase flows coupled with structures relevant around nuclear fuel bundles, e.g. loss of coolant and other accident scenarios, and fluid mixing effects on nuclear urban consequences; and, 6) flow behavior of esoteric materials under extreme conditions whereby these materials undergo a range of behaviors and states from cold and strong solids, on to hot fluids, and then to mixed ionized and partially ionized plasmas.
A full quantitative understanding of either the macroscopic or microscopic properties must rely on an effective integration of theory, experiments, and numerical simulations. A balanced investment approach should be used in the development of these areas.

Radiation flow and material interaction

LANL continues to have an extensive and world recognized presence in thermal radiation transport theory and simulation, culminating in several advanced capabilities based on Monte Carlo and discrete ordinates methods. These are also used in conjunction with faster low order methods to increase solution time without loss of accuracy. Coupling of these to modern hydrodynamics codes with thermonuclear, fusion reactions and realistic material properties provides high fidelity solutions to high energy density regimes found in ICF, NIF, and astrophysical applications.

There has been significant progress in our ASC codes in improving the simulation capabilities and fidelity for stockpile assessment and modeling. However, continuous validation of physics models in our ASC codes is critical for the stockpile stewardship program. To facilitate this effort, realistic physics models with improved fidelity must be implemented in our ASC codes to model, design, and analyze HEDP experiments conducted on NIF and other facilities.

Plasma dynamics and magneto-hydrodynamic phenomena

LANL has significant capability in MHD simulations which have been applied to magnetized target fusion research, explosive flux compression generator physics design, and pulsed power driven magnetic liner implosion dynamics. These capabilities are crucial in understanding HED plasma matter and energy transport, effects of self-generated electromagnetic fields, and instabilities (shock driven or otherwise). Together with our *ab initio* plasma particle and molecular dynamics simulations, LANL is well positioned to answer questions of the fundamental properties of warm dense matter, plasma kinetic effects on thermonuclear burn , transport properties (e.g., heat conductivity, viscosity, particle stopping), non-equilibrium atomic and radiative physics.

Multi-dimensional simulation codes with resistive MHD capability are crucial in modeling HEDP experiments and this effort deserves a high priority. The ability to model high convergence ratio in capsule implosion will broaden the applicability of our ASC codes in modeling HEDP experiments on NIF. In addition, with the continued advances in computing power, an opportunity exists to pursue a numerical simulation methodology at grand challenge scale in integrating particle-in-cell technique with molecular dynamics method to model physics phenomena in a first-principle manner.

Computational techniques and solutions

To adequately model phenomena in HEDP and Fluids, LANL must pursue advanced numerical simulation capabilities with integrated multi-physics and multi-scale. We must continue to explore novel numerical algorithms and solution techniques for the next computational platforms. There is an area with significant overlap with the IS&T pillar.

7. Conclusion

Working in concert with the community described above, we have defined the Nuclear and Particle Futures (N&PF) pillar to be composed of four major thrusts: Nuclear, Particle, Astrophysics, and Cosmology (NPAC), Applied Nuclear Science and Engineering (ANS&E), High Energy Density Plasmas and Fluids (HEDP&F), and Accelerators and Electrodynamics (A&E). These four thrusts provide the underlying fundamental research and technological developments crucial to successfully advance Defense Programs weapons research, the nuclear component of threat reduction, and the pursuit of high priority fundamental research as identified in the strategic plans of Office of Science programs in Nuclear Physics, High Energy Physics, and Fusion Energy Sciences.

This pillar supports the underlying research required to maintain Los Alamos as the premier laboratory in the USA for all-things nuclear. The community has identified significant areas of overlapping research goals that will serve to strengthen the internal collaboration within the pillar and will enhance the scientific contributions to the major programmatic themes of LANL: weapons, global security, and Office of Science research. The research priorities of the pillar will be defined in the strategic investment planning that is the next step in this process. This set of priorities will be used to guide some of the institutional (e.g. LDRD) and programmatic investments, and it is likely that priority areas will evolve from year to year. The metrics that will be used in this pillar to establish goals and priorities are: Why LANL, why now?; Are we leaders, do we need to be a leader? Where should we partner?; Will investments be creating new opportunities?; and Is it great science? Is it vital for future mission?